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Distribution domains of the Pan-African event in East Antarctica and adjacent areas

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Abstract The Pan-African event is widely distributed in East Antarctica (EA) craton, including both the coastal regions and interior of the EA. From aspects of the shear zones, granites, pegmatites, time of high-grade metamorphism and detrital zircon age peaks of the downflowing sediments from the inland, the Pan-African event in the EA and adjacent areas in the Gondwana reconstruction, like SE Africa, southern India and SW Australia, was described in the paper. The water or fluid available along the shear zones was responsible for retrogression of the earlier, e.g., Grenville age, high-grade outcrops to later Pan-African amphibolite to granulite facies metamorphism. In geochemistry, the granites are generally anorogenic, ocassionally with some gabbros or dolerite dykes, showing sign of bimodal feature. Meanwhile, the event has influenced most isotopic systems, including the U-Pb, Sm-Nd, Rb-Sr and Ar-Ar systems, giving Pan-African apparent ages. Spatially, the Pan-African event is demonstrated from possibly local granitic magmatism, to wider medium-high grade metamorphism, and mostly widespread in resetting for some isotope systems, suggesting the prevailing thermal effect of the event. Before Gondwana formation, local depressions in the EA may have been filled with sediments, implying the initial breakup period of the Rodinia. The later Pan-Gondwana counterrotating cogs shaped the interstitial fold belts between the continent blocks and formed a set of shear zones. The mafic underplating in the Gondwana may be responsible for the typical features of the Pan-African event. The event may be an overwhelmingly extensional and transcurrent tectonics in mechanism and is a possible response of the plate movement surrounding the continent swarms in the non-stable interior of the yet consolidated Gondwana.

Keywords **Pan-African event, distribution, granite, metamorphism, East Antarctica**

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1 Introduction

The term "Pan-African event" was coined by Kennedy (1964) on available Rb-Sr and K-Ar age data from Africa and then was taken as a possible tectono-thermal event *ca.* 500 Ma ago. The Brasiliano Orogeny timely correlating with the event, so the term is also called Brasiliano-Pan-African Orogeny, or different local names, such as Brasiliano event in South America, Adelaidean event in Australia and Beardmore event in Antarctica. The concept has been extraploted to the whole Gondwanaland, or called Pan-Gondwana event (Veevers, 2003), but not used in North America or Asia.

The Pan-African Orogeny means the tectono-thermal activity in the crust at 600–500 Ma, 650–550 Ma or even 950–500 Ma during which the Gondwana formed (Kröner and Stern, 2004; Stern, 1994). The Gondwana accretion took place over a broad period from ~850 to 520 Ma (e.g., Grunow et al., 1996; Dalziel, 1991), with the main accretion occurring from 650 to 520 Ma (Collins and Pisarevsky, 2005; Meert, 2003). The East African Orogeny (EAO), with closure and convergence in the Mozambique suture that peaked at *ca.* 620 Ma (Meert, 2003), assembled the western Gondwana. While the East Gondwana was united together

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through a second suture, or the Kuunga Orogeny of Meert et al. (1995), radiated from Dronning Maud Land (DML) (Jacobs et al., 1998), due to the oblique collision between the Australia-partial EA and some blocks in Eastern African Orogeny (Meert, 2003; Boger et al., 2001).

As the widespread distribution and long-term duration, the Pan-African event was not taken as a single orogeny. It is actually a prolonged orogenic cycle involving the opening-closing of giant ocean basins and accretion and collisions of the drifting continental blocks. Now the term Pan-African Orogeny is specially used in describing the intra-Gondwana tectonic belts with magmatism and metamorphism between the pre-Gondwana blocks in the Neoproterozoic to Early Paleozoic period. Timely the orogeny corresponded with the peri-Gondwana Cadomian and Avalonian orogenies (700–540 Ma) in central-western Europe, where the collision feature is not prominent (Murphy and Nance, 1991).

In the domains with the Pan-African event, two types of principally orogenic or mobile belts can be discerned (Kröner and Stern, 2004). One type is dominated by Neoproterozoic crustal and magmatic rocks (mostly juvenile or mantle derived) which show tectono- metamorphic feature of the collision and accretion belts of the Phanerozoic. The rocks mostly involved are the middle-upper crust of the region, like the ophiolite suites, granites associated with subduction or collision, arcs or passive continental margin assemblages, and some exotic terranes. These units have been modelled with the Phanerozoic plate tectonics, such as the Arabian plate and Arabia-Nubian shield in northeastern Africa. Another type is the mobile belt including polymetamorphosed high-grade metamorphic assemblages from the middle-lower crust of the region, and the origin, setting and tectonic evolution are rather difficult to decipher. The protoliths are mostly Mesoproterozoic to Archean with strong reworking in the Neoproterozoic. The well studied example is the Mozambique belt (including the Madagascar extending to western Antarctica) in eastern Africa.

As a continent with strong demonstration of the Pan-African event (Boger et al., 2001; Fitzsimons, 2000; Zhao et al., 1992), EA was situated at the center of the eastern Gondwana (e.g., Meert, 2003), and was taken as a keystone in Gondwana reconstruction (e.g., Zhao et al., 1995, 1992). Fitzsimons (2000) realized that the East Antarctic shield behaved as a collage rather than a keystone during the amalgamation of Gondwana. Boger et al. (2001) stressed the Pan-African orogenesis was not confined to the coast and may bisect the EA in the Gondwana. The paper will focus on the effect and possible mechanism of the event in EA and adjacent fragments in Gondwana reconstruction.

2 Distribution of the Pan-African event in the East Antarctica

In EA, Stüwe et al. (1989) reported the Pan-African greenschist facies metamorphism in the Larsemann Hills, Prydz Bay. Afterwards, the 550–500 Ma medium-high grade metamorphism event was discerned dominately in the area (Fitzsimons et al., 1997; Carson et al., 1996; Hensen and Zhou, 1995; Zhao et al., 1995, 1993, 1992). Other places in EA have signified the Pan-African activity and a Pan-African suture zone associated with the final assembly of east Gondwana (Fitzsimons, 2003; Harley, 2003; Boger et al., 2001; Fitzsimons et al., 1997; Hensen and Zhou, 1997; Zhao et al., 1992, 1995). The conclusion was put forward primarily based on the decompression-dominated metamorphic P-T paths in the regions evolved during a Pan-African (~530 Ma) metamorphic event (Fitzsimons, Carson et al., 1997, 1996). In contrary, the Prydz Belt was also believed as a Pan-African intraplate orogen related to intracontinental reworking (Tong et al., 2014; Phillips et al., 2009; Wang et al., 2008; Wilson et al., 2007; Yoshida, 2007) due to the recognition of both the ~1000 Ma and ~530 Ma metamorphic events in the paragneisses (Tong and Liu, 1997; Dirks and Hand, 1995). In addition, detrital zircon age data have been used to discuss the possible distribution of the Pan-African domains in EA (e.g., Elliot et al., 2015; Veevers and Saeed, 2011). Combining geology of bedrock, detrital zircon age data and some geophysical information, the manuscript is mainly focused on the distribution and feature of the Pan-African event in the EA and adjacent areas, covering the major areas from 0°, with some west Antarctica, to 180° in longitude in the EA (Figure 1).

2.1 The Shackleton Range

The Shackleton Range is a composite terrane affected to various degrees by the Paleoproterozoic Kimban orogeny, the Mesoproterozoic Grenvillian orogeny and the Late Neoproterozoic/Cambrian Pan-African orogeny (Figure 2, Will et al., 2009). In the south, the Read Complex experienced only orogeny in the Paleoproterozoic. The other parts of the Southern Terrane underwent magmatism between 1850 Ma and 1810 Ma and medium- to high-grade metamorphism event at 1710–1680 Ma and, locally, again at 510 Ma (Will et al., 2009). The Eastern Basement has experienced both the Paleoproterozoic and the Grenville (*ca*. 1060 Ma) events, with local 616 Ma age from the grey margin of zircon CL image. The northern Herbert Mts suffered the Pan-African event only. In the Meade Nunatak and NE Shackleton Range, two distinct age groups were obtained, *ca*. 1700 Ma of monazite and *ca*. 500 Ma U-Pb data of monazite and zircon, Sm-Nd garnet dating and Rb-Sr biotite analyses. In the latter period the Pan-African event manifested peak P-T conditions of about 650ºC, 7.0 kbar, and a retrograde stage at some 575ºC, 4.0 kbar, i.e., of MT/MP amphibolite-facies metamorphism (Zeh et al., 2004).

The Northern Terrane is characterised by 530 Ma old granites and diorites (Will et al., 2009), which are hosted within paragneisses as well as mafic and ultramafic rocks.

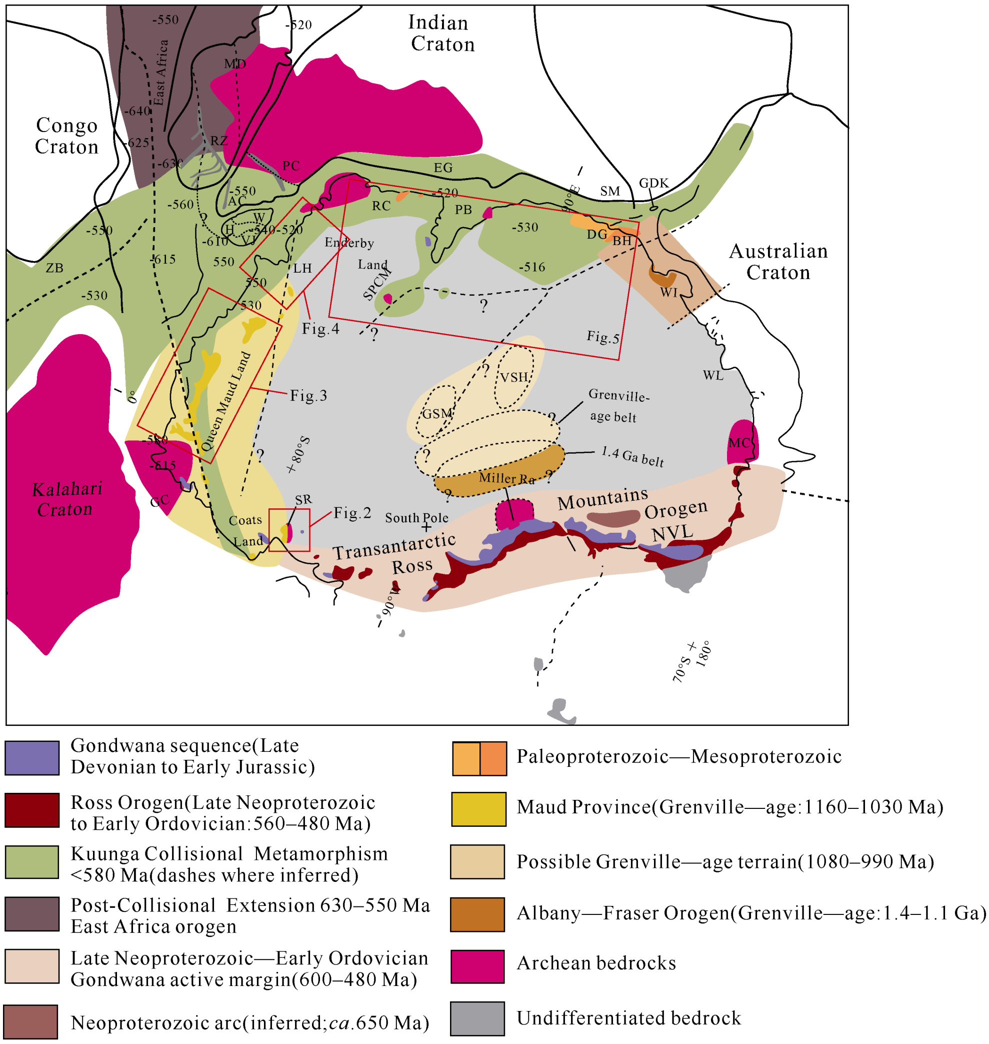

Figure 1 Geographic distribution of East Antarctica and adjacent continents in Gondwana reconstruction (modified after Liu (2018), Elliot et al. (2015), Meert (2003)). The dashed lines mean proposed sutures or shear zones. Abbreviations: AC–Achancovil Suture Zone; BH–Bunger Hills; DG–Deman Glacier; EG–Eastern Ghats Land; GC–Grunehogna Craton; GDK–Gulden Draak Knoll (magnified); GSM–Gamburtsev Subglacial Mountains; H–Highland Complex; LH–Lützow-Holm Bay; MC–Mawson Craton; MD–Madagascar; NVL–Northern Victorian Land; PB–Prydz Bay; PC–Palghat-Cauvery Shear Zone; RC–Rayner Complex; RZ–Ranotsara Shear Zone; SM–Shillong-Meghalaya Plateau; SPCM–Southern Prince Charles Mountains; SR–Shackleton Range; VJ–Vijayan; VSH–Vostok Subglacial Highlands;W–Wanni Complex; WI–Windmill Islands; WL–Wilkes Land.

In summary, the Pan-African event in the Shackleton Range shows obvious tendency of high intensity in the north, but weak in the south. All rocks of the Northern Terrane experienced upper amphibolite- to granulite-facies and, locally, eclogite-facies metamorphism (Schmädicke and Will, 2006) later at 510–500 Ma. This event resulted from the subduction of the paleo-Pacific ocean (Will et al., 2009).

2.2 The DML and Sør Rondane Mts

In the Coats Land, the comparison of aeromagnetic data and crustal provinces indicated that the basement was likely to be composed of pre-Mesoproterozoic formation which has been differentially reworked at *ca*. 500 Ma within the East African/Antarctic Orogen. The western orogenic front of the East African/Antarctic Orogen was exposed as the Heimefront Shear Zone of mylonitization at amphibolite facies conditions, while the eastern orogenic front might be represented by the Otter Highland Thrust in the Shackleton Range, with variably reworked crust up to granulite facies in between these two structural discontinuities (Jacobs et al., 2003).

In wSRestern DML, a major extensional shear zone was dated at 507±9 Ma, and late-tectonic granitoid intrusions of high-temperature A2-type granitoids (post-orogenic) indicate crystallization ages of 501±7 and 499±4 Ma (Jacobs et al., 2008). High-grade metamorphic recrystallisation and metamorphic zircon overgrowths at approximately 530 Ma and was followed by late- to post-tectonic magmatism, reflected by 500 Ma granite bodies and 490 Ma aplite dykes as well as a 480 Ma gabbro

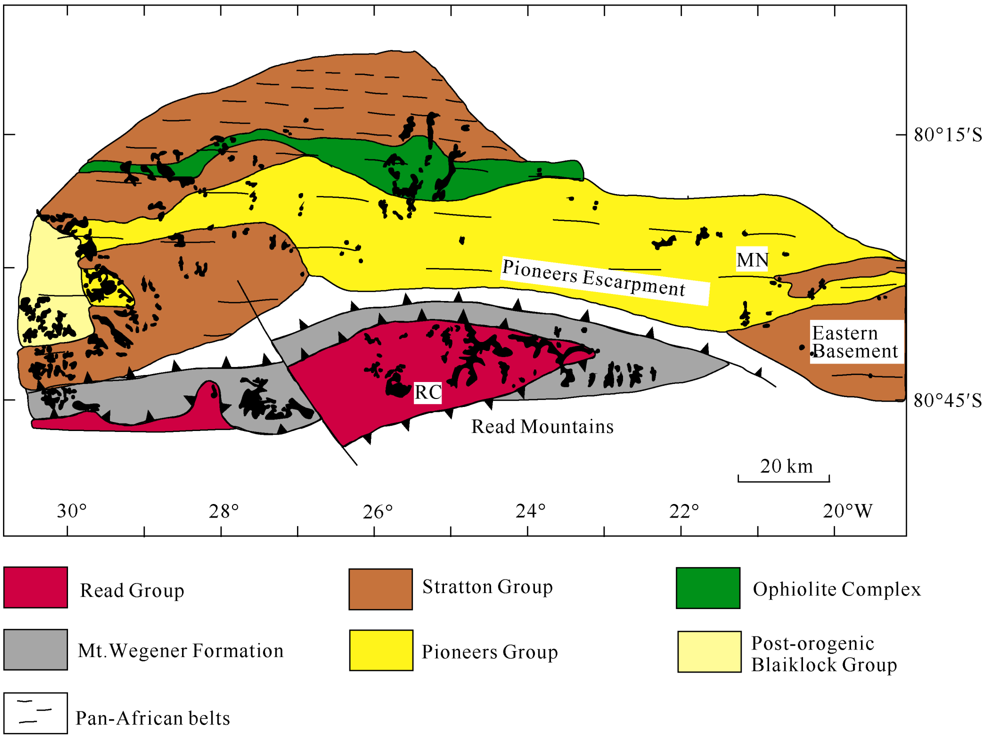

Figure 2 Tectonic sketch map of the Shackleton Range (modified after Will et al. (2009)), showing the possible distribution of the Pan-African event. MN–Meade Nunatak; RC–Read Complex.

body (Bisnath et al., 2006). In the DML, the extensional dextral shearing prevailed and the 560–550 Ma parallel granitic pegmatite swarms were emplaced along normal faults under a regime of NNE-SSW horizontal extensional stress.These pegmatite swarms were considered to have been the heralds of the voluminous 530–500 Ma A-type granite intrusions in DML (Toyoshima et al., 2013). The granites were a little younger than the A-type granites (580－550 Ma) in the Sør Rondane Mts. In the central DML, the late Pan-African high-grade metamorphism (Jacobs et al., 2003) gave a near-IBC path following ITD (Ravikant, 1998) and syn- to post-orogenic magmatic evolution (Paulsson and Austrheim, 2003), which closely resembles those of the Grove Mountains (Liu et al., 2006).

The magmatic province is bounded in the north by the Lurio Belt in the SE Africa in Gondwana reconstruction (Meert, 2003), and the late-tectonic granitoid sheets and plutons from the Nampula Province with age of *ca*. 510 Ma, therefore, the late-tectonic magmatism can be bracketed between *ca*. 530 and 485 Ma. The magmatic province started with small gabbro bodies emplaced at *ca*. 530–520 Ma, culminated with the intrusion of major granite–charnockite plutons at *ca*. 510–500 Ma. The ancient current flow indicates that the detrital zircons of 700–500 Ma were sourced from the south (Veevers et al., 2008a, 2008b), implying the wider distribution of the Pan-African event than the DML (Jacobs and Golynsky, 2001) (Figure 3).

In the Sør Rondane Mountains (SRMs) (Figure 3), the high-grade metamorphic rocks and orthogneisses gave the zircon ages of 1970–1870 Ma in the northeast and *ca*. 1000 Ma in the southwest, and the zircons were considered as inherited in origin (Osanai et al., 2013). Acually, similar zircon age pattern has been present in the southern Lützow-Holm Bay to the east (Takahashi et al., 2018). As a whole, the SRMs were occupied by 640–600 Ma granulite- facies metamorphism and transitional retrogression (680–700ºC and 8.5 kbar, Baba et al., 2013) and syenitic granite in the central, wheras amphibolite-facies metamorphism and obvious 570–520 Ma granites in the southwest (Adachi et al., 2013). The SW and NE terranes of the SRMs were brought together during amphibolite-facies metamorphism at *ca.* 570 Ma (Shiraishi et al., 2008), or 600 Ma (Osanai et al., 2013), and share a common metamorphic and magmatic history from that time. High-grade metamorphism was followed by extensive A-type granitoid activity and contact metamorphism between 560 and 500 Ma. As to zircon Hf isotopic compositions of the granites, only transitional changes between different terranes were measured, with lower initial ε_{Hf} values toward the northeast in SRMs (Elburg et al., 2016). These Lu-Hf isotopic age data of zircons from the 580–550 Ma granites (juvenile input) suggest the possible mantle factor in the period. With the presence of mafic and silica-undersaturated intrusives, the period shows more involvement of juvenile input than the other periods of 650–600 Ma (crustal reworking) and *ca*. 530 Ma, and a magmatic tail between 510 and 500 Ma (Elburg et al., 2016). The voluminous granites along the SE SRMs may represent the Pan-African domain, with the center in the central to SW SRMs (Figure 3).

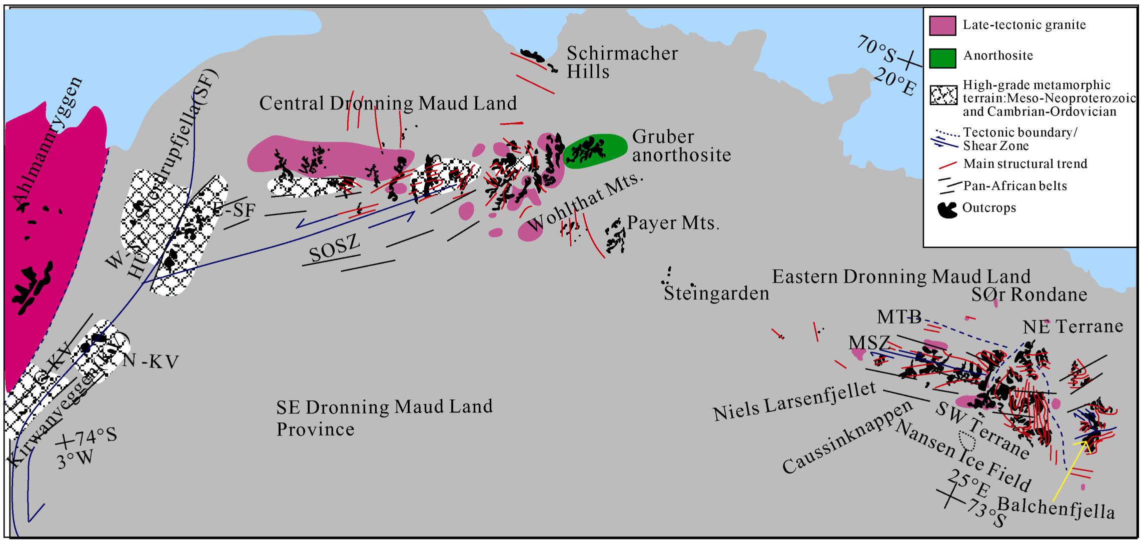

Figure 3 Simplified geological map of the SRMs (modified after Jacobs et al. (2017), Grantham et al. (1995)), and possible demonstration of the Pan-African event.

2.3 The Lützow-Holm Bay and neighbouring areas

In the Lützow-Holm Bay Complex (LHC), the Late Neoproterozoic to Cambrian (619–486 Ma) metamorphic ages were obtained from structureless zircon grains and/or homogeneous rims, mantles, and rarely cores with lower Th/U ratios than detrital grains (Takamura et al., 2018). The results are consistent with the contention of a Late Neoproterozoic regional metamorphism in the LHC (e.g., Kawakami et al., 2016; Tsunogae et al., 2016). The eastern margin of the complex not exposed, but is presumed to continue to the western Rayner Complex, which corresponds to a Meso- to Neoproterozoic terrane reworked during the Neoproterozoic (e.g., Satish-Kumar et al., 2008). To the east, emplacement of post-tectonic Early Paleozoic (*ca.* 530–500 Ma) pegmatites on Tonagh Island, Napier Complex, was accompanied by introduction of aqueous low-salinity fluids at mid-P upper-amphibolite facies conditions (*ca.* 8 kbar, *ca.* 680°C), was the indication of the Early Paleozoic event (Carson and Ague, 2008).

The northern Lützow-Holm Bay is similar to the Vijayan Complex (VC) of Sri Lanka (Figure 1) (Takamura et al., 2018; Kröner et al., 2013) in that the granitoid gneisses of *ca.* 1.1–1.0 Ga are dominated, with calc-alkaline geochemical signature, and weak amphibolite-facies metamorphism superposition of Pan-African in the northern LHC, but high-grade metamorphim in the VC. Many zircons experienced slight to significant lead-loss at *ca.* 580 Ma.

The southern LHC was strongly influenced in the Pan-African event (Takamura et al., 2018). To the inland direction, the lower crust beneath the Mizuho Plateau may be attributed to higher abundance of biotite in the mafic lower crustal rocks in which the biotite-bearing assemblages were formed by metasomatic processes associated with Pan-African orogeny (Nogi et al., 2013). The western and southern domains possibly extend towards the Neoproterozoic Yamato-Belgica Complex, where granulite facies metamorphism at *ca.* 660 and 620 Ma, amphibolite facies metamorphism and K-feldspar rich granitic magmatism at *ca.* 540–530 Ma (Shiraishi et al., 2008, 2003). The voluminous granites along the Yamato and Belgica Mts may represent the Pan-African domain (Figure 4). Asami et al. (1997) also reported CHIME ages in the range of 534–531 Ma on monazite in biotite-gneisses from the Yamato Mountains.

2.4 The northern Prince Charles Mountains

The Pan-African event is scatterly distributed in the northern Prince Charles Mountains (nPCM) (Figure 5), and the superposition pattern of the event has not been fully elucidated (Morrissey et al., 2016; Boger et al., 2002; Carson et al., 2000; Hensen and Zhou, 1997; Zhou and Hensen, 1995; Manton et al., 1992; Tingey, 1991). Intrusions of granite and pegmatite occurred at the range of 550–500 Ma (Boger et al., 2002; Carson et al., 2000; Manton et al., 1992), and partly migmatized (Scrimgeour and Hand, 1997; Hand et al., 1994). Some mylonite zones of NE strike give amphibolite-facies metamorphism conditions (524±20°C, 0.76±0.4 GPa) (Boger et al., 2002; Carson et al., 2000; Manton et al., 1992). Nevertheless, most samples have shown minor resetting in the zircon U-Pb isotope system, without substantial Pan-African zircon growth (Kinny et al., 1997; Manton et al., 1992). The Rb-Sr system was reset to *ca.* 500 Ma (Manton et al., 1992; Tingey, 1991), while the Sm-Nd system of the garnet was reset to 825–555 Ma (Hensen and Zhou, 1997; Zhou and Hensen, 1995).

The Pan-African event is dominately manifested in the garnet-sillimanite-cordierite gneiss in the Taylor Platform, Brocklehurst Ridge and Mount Meredith (Morrissey et al., 2016). To the north, the *ca.* 930 Ma event prevailed with minor corona of cordierite, spinel and ilmenite developed and accompanying Pan-African pegmatite in the garnet-sillimanite gneiss in the Depot Peak, Else Platform and Reinbolt Hills. The intensity of the event seems to decrease westwards and northwards. Meanwhile, the 565, 524 Ma A-type granite dykes and veins crop out in the Jetty Peninsula (Mikhalsky et al., 2001), and the 548 Ma felsic dykes in the Beaver terrane (Boger et al., 2002). No Pan-African sign occurs in the Mawson Coast adjacent the Mawson Station of Australia, while to the further west or at the boundary between the Rayner and Napier Complex, the Pan-African event re-appears (Kelly et al., 2012). To the south, the event has not been detected in the Fisher terrane (Morrissey et al., 2016), thus we can infer that the Pan-African event in the nPCM is strongest along the line from the Taylor Platform to Prydz Bay, with occurrence of the earlier Mt Meredith granites of 551 Ma and 546 Ma (Laiba et al., 2006). The Taylor Platform to Prydz Bay zone may be central line to one of the Pan-African domains in the EA.

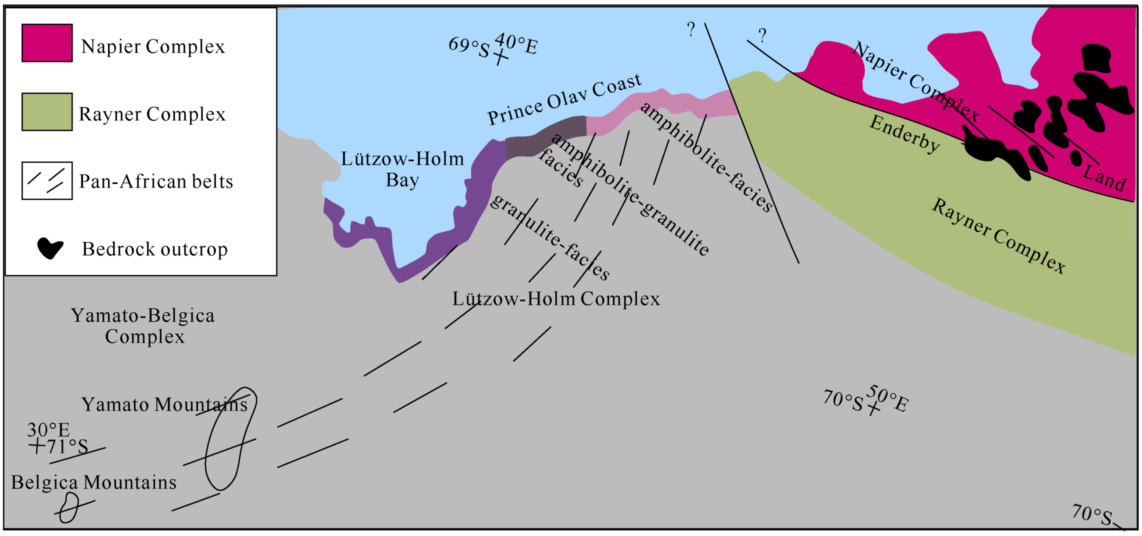

Figure 4 Map that gives an overview of geographical names and geological terranes around the Belgica Mountains, Yamato Mountains, Lützow-Holm Bay, Prince Olav Coast and western Enderby Land (Modified after Toyoshima et al. (2013), Carson and Ague (2008)), and the possible demonstration of the Pan-African event.

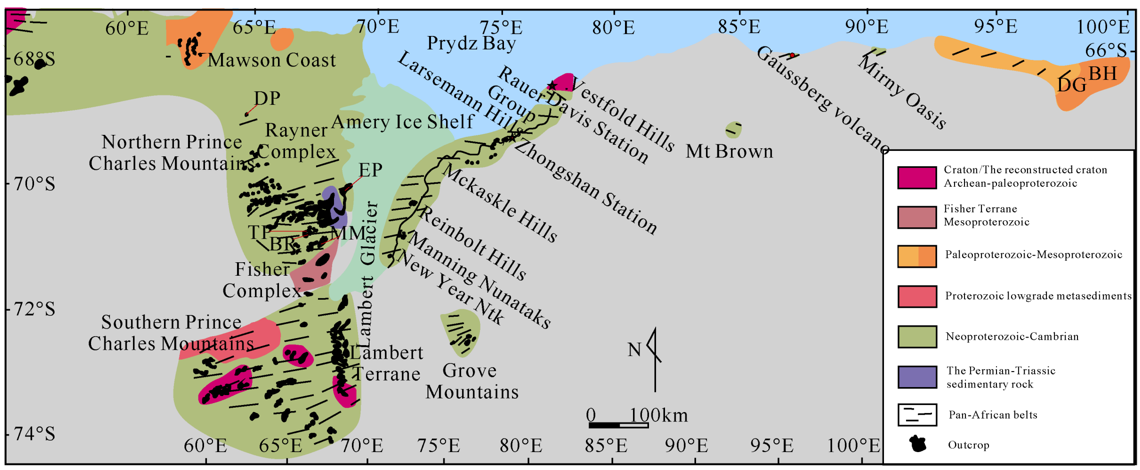

Figure 5 Simplified geological map of the Mawson Coast to Prydz Bay, Bunger Hills of the East Antarctica (modified after Liu (2018), Morrissey et al. (2016), Sheraton et al. (1995)), and possible demonstration of the Grenville and Pan-African events. Abbreviations: BH–Bunger Hills; BR–Brocklehurst Ridge; DG–Denman Glacier; DP–Depot Peak; EP–Else Platform; MM–Mount Meredith; TP–Taylor Platform.

2.5 The southern Prince Charles Mts and Grove Mts

The Lambert terrane (to the north of Harbour Bluff) in the southern Prince Charles Mountains (sPCM) (Figure 5) is a Paleoproterozoic basement (Mikhalsky et al., 2010, 2006; Corvino et al., 2008), which was reworked during the Pan-African event at upper amphibolite-facies metamorphism (peak P-T conditions of 630–700ºC, 0.6–0.7 GPa, Phillips et al., 2009, Boger and Wilson, 2005). The event was also manifested with localized shear zone development and/or reactivation and the sporadic emplacement of pegmatite and granitic sheets (Corvino et al., 2011, 2008; Mikhalsky et al., 2006). Similarly, in the sPCM deformation involved the development of kilometre-scale upright open folds and subvertical high strain zones (Phillips et al., 2009, Boger and Wilson, 2005), while the rocks show pervasive recrystallization and amphibolite-facies metamorphism during the event (Phillips et al., 2009). In the central Mawson Escarpment, the A-type granite gives the Rb-Sr whole rock isochron 551±74 Ma (Sheraton et al., 1995). Deformation and contemporary amphibolite-facies metamorphism took place at 510 Ma (Boger et al., 2008).

In comparison, the Ruker terrane experienced different styles in the Pan-African event for the basement and cover. The Archean Ruker Complex has undergone localized high straining accompanied with amphibolite facies metamorphism (peak conditions of 565–640°C, 0.4–0.52 GPa, Phillips et al., 2007), and the time of deformation and metamorphism is constrained to 504–488 Ma by $^{40}Ar/^{39}Ar$ mica thermochronology (Phillips et al., 2007). On the contrary, the cover sequence of the Sodruzhestvo Group has been deposited after *ca.* 950 Ma, as constrained by the youngest population of detrital zircon (Phillips et al., 2006). A single phase of shortening folded the Sodruzhestvo Group into upright to reclined NW-trending structures, with greenschist facies metamorphism (Phillips et al., 2009). That is to say, the Pan-African event was strongly developed in the south, but weakly in the north, which led Boger et al. (2001) to conclusion that a collision zone in the sPCM was the cause of this Early Palaeozoic reworking. Due to the weak manifestation of the event in the Fisher terrane (Morrissey et al., 2016; Phillips et al., 2009), the nPCM and sPCM may correspond to different Pan-African domains.

In the Grove Mountains, the NE-NNE strike normal faults or shearing zones are more remarkable, though earlier compression may have taken place (Hu et al., 2008). The charnockite, granite and dykes of similar compositions had been emplaced in succession during the period from 550 to 500 Ma (Liu et al., 2006). Trace element abundances indicate that all the granitoids are of A-type affinity, characterized by enrichment in REE, Y, Ba, Sr, Ga and HFS elements (Zr, Nb, Th), suggesting derivation from a long-term enriched subcontinental lithospheric mantle, i.e., the substantial involvement of the crust materials in granitization. In addition, the isotopic compositions of the granitoids are very similar to those of the Pan-African syenitic rocks from David Island, west of Denman Glacier (Sheraton et al., 1992), implying the possible boundary of the Pan-African scope. Actually, the Rb content is higher in the southern Grove Mts (Li and Huang, 2018), which is consistent with the more outcrops of the charnockite in the southern part (Liu et al., 2006).

2.6 The Amery Ice Shelf and Prydz Bay region

Since recognition of the 550–500 Ma medium-high grade metamorphism in the Larsemann Hills, Prydz Bay (Figure 5), the Pan-African terranes (or Prydz orogenic belt) were distinguished from the Rayner Comlex in the EA (Fitzsimons et al., 1997; Carson et al., 1996; Hensen and Zhou, 1995; Zhao et al., 1995, 1993, 1992, 1991). The high-grade Pan-African event in the Prydz Bay was mainly manifested with the zircon U-Pb ages of 516–514 Ma (Carson et al., 1996) from the syn-deformation granite which was considered as post-orogenic A-type granite (Li et al., 2007). The zircon and monazite ages of 536–527 Ma from the leucocratic anatexis gneiss (Fitzsimons et al., 1997; Zhang et al., 1996) and the garnet-whole roch Sm-Nd isochons of 517–490 Ma from the orthogneiss or paragneiss (Hensen and Zhou, 1995), all were of Pan-African period.

In the Amery Ice Shelf–Prydz Bay region, many SHRIMP zircon ages of metamorphism at the range of 546–512 Ma have been reported (Liu et al., 2014a, 2009, 2007; Grew et al., 2012; Wang et al., 2008). The sillimanite-bearing pegmatite along the high-angle normal fault in the Reinbolt Hills produced the monazite U-Pb age of 536±17 Ma (Ziemann et al., 2005), suggesting extensional setting of the Pan-African event in the region east of the Lambert rift. The similar age 534±7 Ma from the orthopyroxene-bearing gneiss in the New Year Ntk and older zircon U-Pb age of 582±13 Ma up to the Neoproterozoic in the Mistichelli Hills (Liu et al., 2009). In the Neoarchean rocks-dominated Vestfold Hills, the meta-dolerite dykes and wall rocks may give the mineral-whole rock Sm-Nd isochron and the hornblende, biotite $^{40}Ar/^{39}Ar$ plateau ages of 670– 589 Ma and 526–509 Ma, respectively, suggesting the ealier rocks can not avoid reworking of the Pan-African, though the mineral response is needed to be studied (Liu, 2018). Similar situation has been noticed in the Larsemann Hills, like the late amphibole rim on earlier pyroxene (Figure 6). The isotopic system may be more obviously manifested than the metamorphic reactions in the event. As to the younger end, the garnet-whole rock Sm-Nd isochron may be young to 467±8 Ma (Hensen and Zhou, 1995), implying the span of *ca.* 200 Ma of the Pan-African event in the region. Nevertheless, the histogram gives the peak age of *ca.* 520 Ma in the Larsemann Hills (Ren et al., 2016) (Figure 7), which is identical to that of the northern Prince Charles Mountains (Liu et al., 2017), both are similar to that of the Rb-Sr and K-Ar ages peak of *ca.* 500 Ma in the Africa (Kennedy, 1964). With metamorphism and magmatism ages (Ren et al., 2016) separately calculated, we got the peaks of metamorphism (~528 Ma, n=36) and magmatism (~498 Ma, n=15), respectively, in the Prydz Bay region (Figure 7). Furthermore, the successive metamorphism processes lasted with the period of ~100 Ma, while pulsive magmatism was confined to a span of some 55 Ma. Spatially, the Pan-African high-grade event is dominated in the Prydz orogenic belt, while the Grenville event is also present or residual in the area (Fitzsimons, 2003; Harley, 2003; Zhao et al., 2003). The Pan-African event has also affected most of the Amery region (Morrissey et al., 2016; Liu et al., 2014b; Corvino et al., 2008; Phillips et al., 2007; Boger et al., 2002, 2001). In addition, the superposed metamorphism grade of Pan-African varies in different places (Liu et al., 2013), which was accompanied by compression-extension and emplacement of the charnockite and granite (Liu et al., 2009; Li et al., 2007; Carson et al., 1996, 1995; Dirks and Hand, 1995).

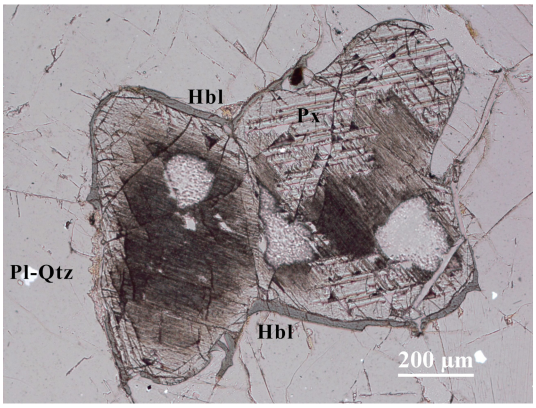

Figure 6 Possible Pan-African amphibole rim superposed on earlier pyroxene, Larsemann Hills, East Antarctica. Abbreviations: Hbl–hornblende; Pl–plagioclase; Px–pyroxene; Qtz–quartz.

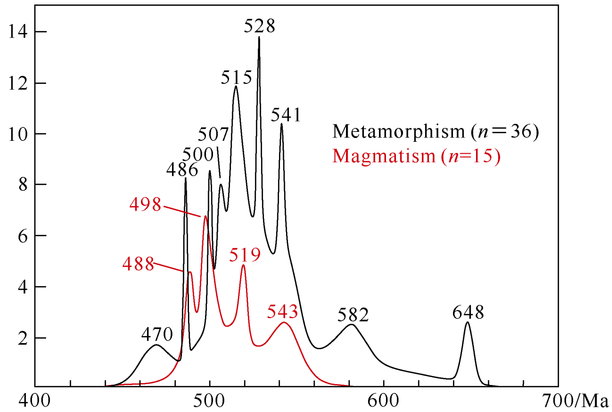

Figure 7 Histogram on time of Pan-African magmatism and metamorphism in the Prydz Bay region, East Antarctica (recalculated from the data of Ren et al. (2016)).

2.7 The Gaussberg volcano to Mirny Oasis coast areas

In the Mirny Oasis along the coastline of the EA, *ca*. 500 Ma post-metamorphic granitoid vein network and pluton emplacement can be found, and the Gaussberg volcanic rocks give zircon population with the same time period, wheras the inland Mt Brown shows no sign of the Pan-African event (Mikhalsky et al., 2015). Liu (2018) analyzed the monazite U-Pb ages from rocks collected at the Mt Brown, obtained the concentration near 900 Ma, and Pb loss in some grains, with some bead-like spots centered at *ca*. 600 Ma on the concordian curve, suggesting the formation age of the monazite in fluid-present setting. Meanwhile, both the rutile U-Pb age of *ca*. 515 Ma and biotite $^{40}Ar/^{39}Ar$ plateau age of 520–505 Ma show the involving of the Pan-African event in the Mt Brown and varying degrees in different rocks or localities, implying the heterogeneity of the event here (Figure 5). That is to say, the event is only manifested by the resetting of some isotopic systems, but the temperature attained or event feature is still poorly understood (Liu, 2018).

2.8 The Bunger Hills and further eastern regions

According to Sheraton et al. (1993), voluminous granites (with zircon U-Pb age of 516.0±1.5 Ma) of post-orogenic A-type feature are present near the Deman glacier (99ºE), such as the syenite or rapakivi at David Island (Black et al., 1992), and further west. But no granites of this period are present in the Bunger Hills and Obruchev Hills (99º–102º E) to the east, where the E-W strike alkaline basic dyke produced the Rb-Sr isochron age of 502±12 Ma (Sheraton et al., 1990). Most of the basic dykes in the Bunger Hills were emplaced ~1140 Ma ago (Rb-Sr and Sm-Nd ages; Sheraton et al., 1990), with some zircon recrystallization and severe Pb loss in inherted zircon during the period of 600–500 Ma. The outcrops west of the Denman and Scott Glaciers preserved the Pan-African granitic magmatism and metamorphism, whereas the Bunger Hills region did not (Sheraton et al., 1993). Thus, the Deman glacier (99º–100ºE) may represent a boundary in the Pan-African event (Figure 5).

Further east in the Windmill Islands (107º–112ºE), bedrock and tillites possibly demonstrate a large terrane of Late Mesoproterozoic with high-grade metamorphism, but without effect of the Pan-African event (Zhang et al., 2012) (Figure 1). In the Wilhelm II Land and Queen Mary Land, part of the Wilkes Land or Mawson continent, no Pan-African record was found. Along the 120º–155ºE coast (including partial Wilkes Land, Adélie Land and George V Land), detrital zircons gave the age cluster of 600–500 Ma (Veevers and Saeed, 2011), suggesting a possible source of Pan-African domain. Roy et al. (2007) and Williams et al. (2007) also obtained minor ~500 Ma $^{40}Ar/^{39}Ar$ hornblende ages in the circum-Antarctic glaciomarine sediment in the Wilkes Land sector (Figure 8).

The Gulden Draak Knoll, located between the western Perth Abyssal Plain and Wharton Basin, Indian Ocean, has been reconstructed in Gondwana (‘Leeuwin’ full-fit model) along strike of a major structure termed the Indo–Australo–Antarctic Suture (IAAS) mapped from geophysical interpretations in Wilkes Land, Antarctica. Cambrian orogenesis prevailed in the Knoll and Cambrian granite was inferred to intruding the metamorphic rocks (Gardner et al., 2015). As rocks from the Gulden Draak Knoll have affinity to crust exposed either side of the IAAS, it is still open regarding whether the structure is a suture or not.

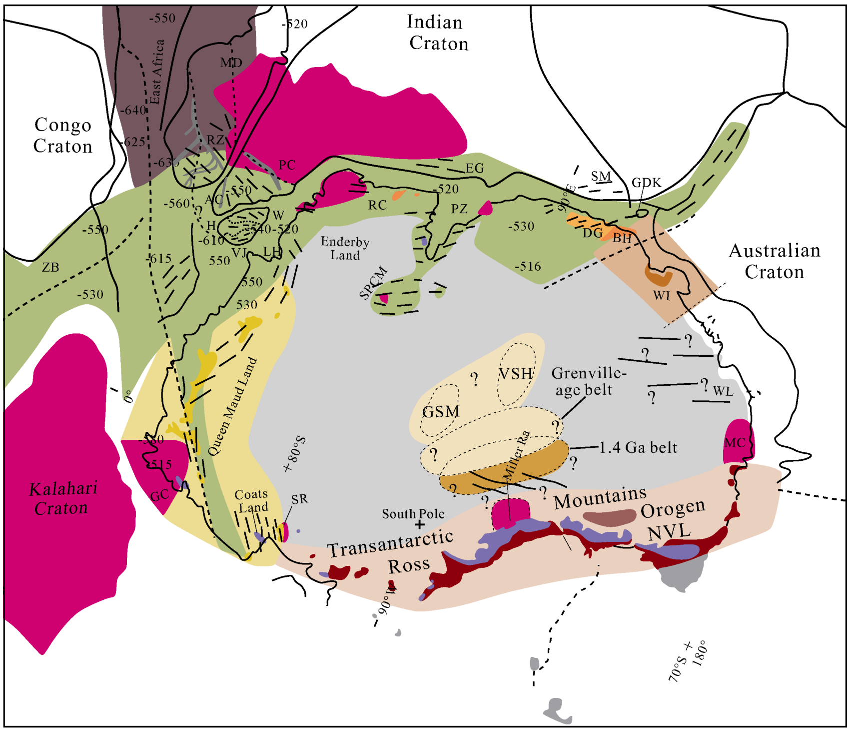

Figure 8 Map of the East Antarctia and adjacent continents in Gondwana reconstruction (modified after Liu (2018), Elliot et al. (2015), Meert (2003)), showing the Grenville and possible Pan-African demonstration domains (the dashed line domains), other legends see Figure 1.

2.9 The Transantarctic Mountains

In the Transantarctic Mountains, the granites and metamorphism of 547–499 Ma or extended to 550－480 Ma took place in the Ross Orogeny (Goodge and Fanning, 2016). Here, the Gondwana sequence in the central part of the range was derived mainly from the ice-covered East Antarctic craton, for which the geology is inferred from coastal outcrops and the Miller Range (Elliot et al., 2015). The sandstone of Pagoda and Fairchild Formations is dominated by detrital zircons of 600–530 Ma age together with a significant Grenville-age cluster (1.3–1.0 Ga) and minor 1.5–1.4 Ga cluster, with a scatter of older ages. Zircons with a Late Neoproterozoic to Ordovician signature (600–460 Ma) were sourced from a Ross Orogen foreland sequence, and/or an early and inland extension of the orogen itself, even the nearby East Antarctic craton. The Grenville-aged source was considered to be, similarly, a subglacial belt in the interior of the EA (Figure 8).

2.10 Central or interior East Antarctia

As covered by thick ice cap, information of central EA are based on the glaciomarine sediments, which have given U-Pb ages of 660–460 Ma from inherited or detrital zircons (Goodge and Fanning, 2010). Furthermore, zircon U-Pb ages from a suite of granitoid clasts collected in glacial catchments draining central EA through the Transantarctic Mountains show that crust in this region was formed by a series of magmatic events from Paleo- to Mesoproterozoic, with the dominant granitoid populations at *ca*. 1.85, 1.45 and 1.20–1.06 Ga (Goodge et al., 2017). None of these igneous ages is known from limited outcrop in the Transantarctic Mountains, nor did the rocks come from the young Phanerozoic accretion orogenies in the west Antarctica (Mukasa and Dalziel, 2000). Therefore, the detrital zircons must have been derived from the interior of East Antarctia. Besides the coastal regions, there must be some Pan-African domains in the interior of the EA. (Figure 8).

Veevers and Saeed (2011, 2008) demonstrated that the central Antarctic provenance about a core of the Gamburtsev Subglacial Mountains (GSM) and Vostok Subglacial Highlands (VSH) contains a basement that includes igneous (mafic granitoids) and metamorphic rocks with peak U-Pb ages of 1.3–0.9 Ga, 0.7–0.5 Ga and some older clusters, especially the former was more widely distributed. Possible terranes of 1.7–1.4 Ga and 2.3–1.9 Ga were inferrd to be confined along the craton side of the Transantarctic Mts. The complex of 1200–800 Ma (Grenville) and older cratons with mafic granitoids were embedded in the 700–500 Ma fold belts with granitoids and alkaline rocks, that is, the GSM-VSH complex is dominated by rocks generated during the Grenville and Pan-Gondwana events during supercontinental assembly.

In EA, the combined Ruker, Vestfold–Rauer, and Princess Elizabeth (R-VR-PE) cratons and the Adélie Craton (AC) were delineated through geophysical mapping, and the GSM-VSH complex was outlined by Veevers and Saeed (2008), and further three cratons were deduced, all set in a matrix of (700–500 Ma) foldbelts (Figure 8). In addition, a systematic comparison between seismic velocities beneath the GSM and similar regions else in the world suggests some Paleoproterozoic or Archean terranes may be underlain the ice cover, corresponding to very old continental lithosphere (Heeszel et al., 2013). Furthermore, these features are not limited to the GSM, but rather they extend across the EA mountain ranges (EAMOR) (An et al., 2015).

3 Characteristics of the Pan-African event in the East Antarctica

Though with ophiolites, eclogite, mélange and granites of possible accretion or collisional belt at 510–500 Ma in the Shackleton Range (Schmädicke and Will, 2006), most of the EA regions seem to have been occupied by reactivated older orogenic belts. The middle-lower crustal rocks in these belts have undergone polymetamorphism and multiple deformation, and the origins and tectonic settings are rather difficult to reconcile. The protoliths were mostly of Archean-Mesoproterozoic sequence and reworked in the Neoproterozoic (Kröner and Stern, 2004). According to Veevers (2003), formation of Gondwana was completed during Pan-African time, but the extent of ocean closure *vs* intracontinental resetting along the various Pan-African belts is controversial (Rogers et al., 1995). The most pronounced features of the Pan-African event in the EA are represented by the occurrence of the shear zones, granitic rocks and superposition of medium-high grade metamorphism to earlier event(s).

3.1 Shear zones

In Gondwana reconstruction, DML was located near the Mozambique Belt in NE Mozambique in southern Africa (Meert, 2003) where occurred a great EW strike Lurio Belt of sinistral shear zone feature (Bingen et al., 2009). There is the possibility of a reversal of trans-orogen asymmetry from sinistral to dextral in the southern part of the EAAO. In the Meatiq Gneiss Dome, in the northern part of the EAAO, major shear zones with high-strain have developed in the quartzofeldspathic gneiss at amphibolites facies metamorphism, with earlier sinistral slip and later extensional faults (Fritz et al., 1996). In Madagascar, many shear zones were exposed (Ishwar- Kumar et al., 2015), like the Angavo–Ifanadriana Shear Zone (AISZ) and the sinistral Ranotsara Shear Zone (RSZ), south of which were occupied by more dense shear zones.

In the central DML, late Pan-African high-grade metamorphism and extensional dextral shearing prevailed and the 560–550 Ma parallel dyke swarms of granitic pegmatite were intruded along normal faults under a regime of NNE–SSW horizontal extensional stress (Jacobs et al., 2003).The earlier sinistral shear zones can be found in the SRMs (Toyoshima et al., 2013).The Balchenfjella area of the eastern SRMs can be structurally divided into two metamorphic units that were separated by a SE-dipping ductile extensional shear zone (the Balchen detachment fault) (Ishikawa et al., 2013). Phases D1 and D2 developed in the footwall side of the shear zone, whereas D3 and D4 were recorded in both the footwall and hangingwall sides. D1 is represented by recumbent folds and this phase is interpreted as a compressional tectonic setting. D2 represents a transpressional deformation phase characterized by upright folds and a large-scale dextral shear zone. The Balchen detachment fault was formed during the extensional tectonic setting of D3 which occurred at *ca*. 600 Ma, and the timing of post-kinematic intrusion of granites (at *ca*. 550 Ma).

Similar to southern Madagascar and Sri Lanka, the southern India occur the Pan-African Palghat-Cauvery Shear Zone (PCSZ) between the southern Dharwar Craton and Madurai Blocks, and the Achancovil Suture Zone (ACSZ) between the Madurai and Trivandrum-Nagercoil blocks (Kröner et al., 2015a, 2015b; Glorie et al., 2014). The khondalites in southern India did not produce any Neo- or Mesoproterozoic detrital grains, their precursor sediments were deposited more than 2.1 Ga ago and were subsequently intruded by granitoid rocks at *ca*. 2100–1765 Ma. Besides, the metasediments were strongly deformed, metamorphosed and migmatized during the period of *ca*. 580–550 Ma (Liu et al., 2016; Kröner et al., 2015a), suggesting the reworking effect of the Pan-African event on earlier terranes. The presence of Archaean rocks on either side of, and within, the PCSZ in India has led to an alternative view of the PCSZ as an intra-continental shear zone (Brandt et al., 2011).

The deformation history of the Pan-African event has been established in the Prydz Bay, where alternating shear zones and composite orthogneisses are distributed (Dirks et al., 1993). In the Larsemann Hills, high-grade, high-strain D3 zones are represented by extensional movement inferred to be parallel to a SW-plunging mineral extension lineations.This extensional episode was correlated with the D4 subhorizontal shear extensional fabrics and flat-lying folds. This phase of deformation was restricted to discrete amphibolite facies, dextral, normal mylonite zones along the margins of NW-trending planar pegmatites (Carson et al., 1997).

The nPCM were thrust from SE to NW (Boger et al., 2002), with the intensity of Pan-African effect wanes northwards and westwards. The Proterozoic basement of the Fisher Complex to the south constrained the generally southwards waning of the Pan-African event. The sPCM demonstrated structural evidence of the Early Palaeozoic event preserved as large (up to ~500 m wide) high strain zones that cut the basement (Tingey Complex) of the Ruker Province (Phillips et al., 2007). At the Mt Harding, Grove Mts, many stages of deformation have been discerned, and asymmetry thrusts and faults from NE to SW imply the earlier thrusting or shearing (Hu et al., 2008).

The Prydz Bay and Napier Complex were situated near the Eastern Ghats Belt (EGB), India, in Gondwana reconstruction (Meert, 2003). Like the Prydz Bay, the Pan-African event has obviously manifested in the Eastern Ghats Belt (Dasgupta et al., 2013). Dobmeier and Raith (2003) stressed that Pan-African tectonics in the EGB was largely focused on shear zones and thrusts reflecting localized intracontinental deformation and intense crustal reworking of the Grenvillian granulites, especially in the Chilka Lake region (Dobmeier and Simmat, 2002). Paleomagnetic data show that the India and Australia-Mawson continental blocks were not united as East Gondwana until after 750 Ma and the amalgamation of blocks was by oblique sinistral transcurrent collision (Powell and Pisarevsky, 2002). Although the earlier shearing is ambiguous, it seems that the late extensional shearing was mostly dextral, that is, there is a reversal of trans-orogen asymmetry from sinistral to dextral in Pan-African orogenic belts.

3.2 Granite, pegmatite, gabbro and bimodal magmatism

The Pan-African event is generally associated with granite and pegmatite, or occasional basic rocks, i.e., possible bimodal magmatism. In the central DML, parallel dyke swarms of granitic pegmatite of *ca*. 560–550 Ma and voluminous 530–500 Ma A-type granite intrusions were intruded along normal faults (Toyoshima et al., 2013), which are a little younger than the A-type granite of the Sør Rondane Mts (580–550 Ma) (Elburg et al., 2016). Late Neoproterozoic/Early Palaeozoic ages show a general younging to the E, with a massive Late Neoproterozoic age peak (850–750 Ma) in the westernmost sample in the DML mountains (Jacobs et al., 2017). The granitoid dyke swarms in DML were considered to have been the heralds of the voluminous 530–500 Ma A-type granite intrusions (Jacobs et al., 2003). In the Lurio Belt and the Nampula Complex, voluminous post-collisional magmatism younger than 530 Ma was present (Bingen et al., 2009). A strong planar, coaxial, high strain WNW-dipping fabric was present in the belt, typically as mylonite, and deformation intensity diminished in the adjacent complexes away from the belt (Ueda et al., 2012). While in the Nampula Province of the southern third of the EAO, small gabbro bodies emplaced at *ca*. 530–520 Ma, culminated with the intrusion of major granite–charnockite plutons at *ca*. 510–500 Ma (Jacobs et al., 2008). The whole Madagascar Island was distributed with the granites of 580–520 Ma (Boger et al., 2015). The Pan-African influence was limited to reheating, tectonic reworking and fluid transfer in the vicinity of Late-Neoproterozoic (~550 Ma) shear zones (Nédélec et al., 2016). The Sankari-Tiruchengode granite (559.1± 3.5 Ma) (Glorie et al., 2014) within the Salem Block north of PCSZ, southern India, has been described as an A-type granite (with high Nb, Zr, Y, Sn, Zn and REE (except Eu) and low Ba and Sr composition), and comprises a leucogranitic and a pink granitic phase (Nathan et al., 2009, 2001). In addition, the Early Cambrian gabbro (*ca*. 540 Ma) has been observed along the ACSZ between the Madurai and Trivandrum-Nagercoil blocks, India (Kröner et al., 2015a).

The SRMs included granites from 650–600 Ma to 510–500 Ma (Elburg et al., 2016). To the east of the LHC, emplacement of Early Palaeozoic (*ca*. 530–500 Ma) post-orogenic pegmatites on Tonagh Island, Napier Complex, has been noticed (Carson and Ague, 2008). As the position of the Tonagh Island at the boundary between the Napier and Rayner Complex, the Pan-African event here may be intracontinental reworking (Tong et al., 2014; Phillips et al., 2009; Wang et al., 2008; Wilson et al., 2007; Yoshida, 2007).

Granites and pegmatite swarms occur along the northern margin of the sPCM (Phillips et al., 2009). The Prydz Bay was widely distributed with Cambrian granites (Liu et al., 2009; Li et al., 2007) and the Grove Mts also show similar situation (Liu et al., 2006). At both the Gaussberg volcano and Mirny oasis occurs the *ca*. 500 Ma granite or inherited zircon of this time.

At David Island to the west of the Bunger Hills, voluminous A-type granites were present (Black et al., 1992), or A1 granite (anorogenic) property on the R1–R2 discrimination diagram (Batchelor and Bowden, 1985) according to the Zr content of the rock (Sheraton et al., 1992). While the alkaline diabase dykes of 502±12 Ma can be observed in the Obruchev Hills, western Bunger Hills (Sheraton et al., 1990), where occurred the mobile belts adjacent the possible Mawson Continent (Fitzsimons, 2003). The Gulden Draak Knoll comprised a high-grade metamorphics and Cambrian granite (Gardner et al., 2015). Anyway, granites and pegmatites of generally A1 granite (anorogenic) property, are the direct manifestation of the Pan-African event in the East Antarctica and adjacent areas.

3.3 Metamorphism in the Pan-African period

As the heterogeneous superposition of the Pan-African event on earlier Grenville orogeny, metamorphism of the Prydz Bay region varied from amphibolite to granulite facies in the Early Palaeozoic (see summary of Liu (2018)). It is rather difficult to discriminate grades of metamorphism in each period. In the Shackleton Range, Pan-African MT/MP amphibolite-facies metamorphism was also reported (Zeh et al., 2004). At Gjelsvikfjella in the western DML, Grenville high-grade metamorphism and Pan-African migmatization and amphibolite facies metamorphism can be distinguished (Bisnath et al., 2006). The Nampula Complex south of the belt underwent amphibolite-facies metamorphism in the period between 543±23 to 493±8 Ma (Bingen et al., 2009). Amphibolite-facies metamorphism prevailed at *ca*. 570 Ma in the SW and NE Terranes of the SRMs (Shiraishi et al., 2008). With granulite facies conditions in the southern Lützow-Holm Bay, the northern part and the Yamato-Belgica Complexes showed amphibolite facies metamorphism at *ca*. 540–530 Ma (Shiraishi et al., 2008, 2003).

The nPCM showed amphibolite-facies metamorphism conditions (Boger et al., 2002; Carson et al., 2000; Manton et al., 1992). In the Lambert Complex, Early Paleozoic granite stocks were present in the south, while the dykes of similar composition in the north (Phillips et al., 2009, Figure 2), suggesting the stronger effect of the Early Palaeozoic Prydz orogenic activity to the south. Rocks away from the zones preserve more complex petrographic textures due to incompletely overgrown by later retrograde assemblages which were highly dependent on the availability of fluid H_2O (Phillips et al., 2009). The Tingey Complex in the western sPCM occurred locally high strain zones in the Early Paleozoic, with the mineral assemblages forming at amphibolite facies metamorphism conditions (4.0–5.2 kbar and 565–640°C of sample at 73° 05.801′S, 66° 14.266′E, Phillips et al., 2009). While rocks of the southern Lambert Complex experienced pervasive deformation and metamorphism at peak conditions (5.8–6.1 kbar and 625–635ºC, sample at 73° 10.917′S, 68° 04.834′E), suggesting the strong activity of the Pan-African at the line between the N and S Lambert Complex. In the Larsemann Hills, the typical demonstration of the metamorphism superposition is the development of amphibole rim on earlier pyroxene (Figure 4).

At the Mirny oasis, the *ca*. 500 Ma orthopyroxene-bearing granite was taken as the evidence of granulite facies metamorphism in the Pan-African (Mikhalskii et al., 2009). In fact, the mafic rocks older than 500 Ma do not show this grade of metamorphism, suggesting orthopyroxene here was derived from the Grenville event, not formed in the Pan-African.

In summary, metamorphism of the Pan-African event in the EA was dominantly manifested with amphibolite facies grade and sometimes accompanying migmatization or granites, with occasional presence of granulite facies metamorphism. On both spatial and temporal aspects, metamorphism effect was distributed in larger area and lasted longer in time than magmatism of the Pan-African event (Figure 7).

3.4 Isotopic resetting with the Pan-African event

The Highland Complex (HC) of the Sri Lankan basement in which the rims of most zircon grains as well as homogeneous grains showed Late Neoproterozoic ages (582–533 Ma) with lower Th/U ratios that can be interpreted as metamorphic origin (Takamura et al., 2016). Meanwhile, the zircons with Pan-African ages often gave grey, black cathodoluminescence (CL) images, suggesting the severe resetting of the isotopic systems. The zircon ages of the VC of E and SE Sri Lanka were predominantly in the range 1100–1000 Ma with a few Early Neoproterozoic intrusions, and experienced minor to significant lead-loss at about 580 Ma (Kröner et al., 2013). At Shillong–Meghalaya Plateau, NE India, homogenous monazite grains in granulite facies metapelites yielded EPMA dates concentrated at 500±14 Ma, but some zoned monazite grains gave the core ages of 1078±31 Ma and 1472±38 Ma, suggesting a northward extension of the Prydz Bay belt (Chatterjee et al., 2007), and the possible Pan-African resetting effect (Figure 1, Figure 8).

In the nPCM, Grenville-aged metamorphism and magmatism dominated and Cambrian metamorphic reworking has been noticed only in one paragneiss (Liu et al., 2017). Early Paleozoic reworking through the whole Prince Charles Mountains and East Amery Ice Shelf region of the Rayner Complex was patchy or selective due to possible hydrous retrogression during the Cambrian (Morrissey et al., 2016; Boger et al., 2001). This resetting in isotopic systems has well demonstrated in the Larsemann Hills (Tong et al., 2018; Wang et al., 2008) and other outcrops in the Prydz Bay (Liu et al., 2009). Zircons from the high gneiss of the Larsemann Hills had black CL images and the average of *ca*. 520 Ma (Ren et al., 2016).

Besides the so-called orogenic belts, the basement or block rocks also showed signs of isotopic resetting in the Pan-African event. At the Tonagh Island, Napier Complex, occurred the aqueous low-salinity fluids at mid-P upper-amphibolite facies conditions (Carson and Ague, 2008).

Afterall, the Early Paleozoic (*ca.* 530–500 Ma) pegmatites and fluid infiltration in the orthogneiss occurred in the Archean basement through reworking, in spite of their possible derivation of the fluid from the underplated sedimentary rocks. In the Vestfold Hills, the mafic dykes and surrounding rocks gave the whole-mineral isochron age and hornblende-biotite $^{40}Ar/^{39}Ar$ age 670–589 Ma and 526–509 Ma, respectively, suggesting the region has been involved in the Pan-African tectonics (Liu, 2018).

Therefore, both the mobile belts and relative stable blocks could have experienced the Pan-African activity, during which isotopic resettingwas most widespread, though sometimes only granitoids or medium-high grade metamorphism occurred. Though not well understood for geodynamic setting of the thermal regime, the retrogression was responsible for some amphibolite facies mineral assemblages and textures, and chemical age resetting of zircon, especially monazite, to some extent during regional "Pan African" tectonism (Kelly et al., 2012).

3.5 Preliminary summary

The Pan-African tectonics in the EA and adjacent blocks in Gondwana reconstruction is represented by the shear zones, granites and pegmatites, mostly of amphibolite facies metamorphism, and resetting of isotopic system.The isotopic system may be more obviously manifested than the metamorphic reactions, and more locally are the granites or pegmatites in the event. The southwards higher intensity of the Pan-African effect in southern India and Madagascar, even along the Lurio belt in the SE Africa (Takamura et al., 2018; Wai-Pan Ng et al., 2017) implies the Pan-African tectonics is heterogeneous, around and inside the EA

(Figure 8) in the Gondwana reconstruction. According to Veevers and Saeed (2011), the Pan-African matrix of foldbelts of 700–500 Ma age were surrounding the cratons.

4 Possible mechanism of the Pan-African event

The Pan-African event in the latest Proterozoic to earliest Paleozoic (~700–500 Ma) was one of the most extensive orogenies in the history of the earth (Mallard and Rogers, 1997). The event is generally taken as a critical movement in Gondwana amalgamation, though with little evidence of ophiolites, arc accretion complex and high pressure rocks (blueschist or eclogite) of sutures or continental collision. The Gondwana was not welded until 530 Ma (Veevers, 2003).

In the EAO, there were perhaps the results of two (or more) tectono-metamorphic events, the earlier collisional (720–620 Ma, Meert, 2003) and the younger extensional one, the later may be as young as 600 Ma (Andresen et al., 2010), which is similar to the Pan-African event in the EA. The amalgamation of the Australia-Mawson continental blocks was by oblique sinistral transcurrent collision (Harris, 1994). The orogeny was resulted from the oblique collision between Australia plus an unknown portion of EA with the elements previously assembled during the East African Orogen. The Prydz orogenic belt along the Prydz Bay to Denman Glacier may represent the collision zone of this orogeny (Figure 1), and the supporting evidence lies in the compression- extensional deformation and near clockwise ITD metamorphic path generally formed in the process of continent-continent collision, crust thickening and subsequent collapse. Another piece of evidence is the different formation time of the Grenville terranes on two sides of the belt and the inconsistency of the palaeomagnetism wander curves of the India and Australia in the Late Neoproterozoic to Early Paleozoic period (Powell and Pisarevsky, 2002; Torsvik et al., 2001). India may have amalgamated with EA long before the Pan-African, and the sutures may be present somewhere, but it is not necessary to be located on either the EA or India. Between India, EA and Australia there was some gap in Gondwana reconstruction (e.g., Meert, 2003), some block(s) may be submerged in the Indian Ocean (e.g., Gardner et al., 2015) or subducted somewhere. An alternative scenario is of intracratonic orogeny (e.g., Yoshida et al., 2003; Tong et al., 2002; Wilson et al., 1997; Yoshida, 1995), which is the response of the EAO within the eastern Gondwana, representing the superposition of the Late Proterozoic to Early Paleozoic on the circum EA Grenville orogeny or local Archean basement. New data of the Wilhelm II Land suggest a continuation of the Rayner Province through nPCM to Prydz Bay, and Wilhelm II Land towards the Bunger Hills area. That is, the Wilhelm II Land was underlain by rock units similar to the Rayner Province in terms of protolith and metamorphic ages and hence against a major Kuunga-age suture running north–south somewhere between the Vestfold Hills and Wilhelm II Land (Mikhalsky et al., 2015). Because no record of subduction related magmatism took place, which would be expected if a large amount of oceanic crust had been subducted. Elburg et al. (2016) noticed a geographic trend with lower initial ε_{Hf} values toward the northeast in the Sør Rondane Mts and the Hf isotopic shifts are gradual, no dramatic change between the two previously defined metamorphic terranes. As a whole, the Pan-African zircon Lu-Hf isotopic data are best explained as reflecting both crustal reworking and juvenile input.

The Pan-African event was responsible for extensive granite magmatism. The widespread granitoids may form due to collapse of possibly thickened continental crusts. Besides deformation and granites of the Pan-African event, the mafic rocks of the same period cannot be ignored, such as the dolerite dyke in the Bunger Hills (Sheraton et al., 1990) and the gabbro in southern India (Liu et al., 2016; Kröner et al., 2015). In the southern third of the EAAO, the Nampula Province started with small gabbro bodies emplaced at *ca*. 530–520 Ma, culminated with the intrusion of major granite–charnockite plutons at *ca*. 510–500 Ma. Actually, the local gabbro intrusions of 530–500 Ma (our unpublished data) after or during the widespread Pan-African granitic magmatism of 540–500 Ma were found in the Jiamusi Block of NE China (Wilde et al., 2003).

The occurrence of the basic and alkaline magmas in the crustal fragments during the Pan-African indicates the possible extensional collapse setting, accompanying the high-temperature A-type granites, alkaline plutons and anorthosites, retrogression metamorphism of the older metamorphics. Adding with the mantle-derived signature of fluids, the extension feature is deduced, such as asthenospheric upwelling or probable underplating of magmas at the base of the continental crust (Santosh and Yoshida, 2001). The contemporaneously extensional shearing and structural styles, granitoid intrusions and geochemical compositions, all indicated partial delamination of the orogenic root (Jacobs et al., 2008). Without syncollisional granites, the widespread thermal rejuvenation, shear zone activation and anorogenic magmatism peaked at 500 Ma and affected most of West Gondwana and localized regions of East Gondwana (Unrug et al., 1994).

In South America, rapakivi granites formed during the Brasiliano orogen, or Pan-African orogen, at 600–550 Ma, and massifs developed from fayalite- or magnetite-bearing magmas (Galindo et al., 1995). They all recorded a close association with large ductile shear zones that extend over thousands of kilometres through NE Brazil and W Africa. In NE Brazil, the plutons are located at the intersection of two major shear zones (Archanjo et al., 1998). The process is inconsistent with substantial continental collision or fragments amalgamation. The extension may be compensated with some sediments, followed by deformation, especially the shear zones, with ubiquitous granites and local gabbros and mostly amphibolite facies metamorphism, and final epeirogenic denudation of the Gondwanaland. In northern Australia, the situation was formed by flood basalt eruption, all represented by a high velocity, reflective lowermost crustal layer (Veevers, 1995).

Pannotia or Greater Gondwana was a relatively short-lived Neoproterozoic supercontinent that formed at the end of the Precambrian during the Pan-African orogeny (650–500 Ma) (Bond et al., 1984), heat release would preferentially result in rifting, leading to Iapetus Ocean formation that splits apart the former supercontinent at 560 Ma (Gardner et al., 2015; Vigneresse, 2005; Bond et al., 1984). Veevers (2003) stressed the possibly initial backarc spreading of the paleo-Pacific took place at 560 Ma. The closure of the Iapetus ocean basin in the Early Cambrian, or the 550–490 Ma oblique subduction of paleo-Pacific ocean floor beneath Antarctica was responsible for the counterrotating cogs and shear deformation in the Transantarctic Mountains and northern Australia. The oceanic crust formed was subducted westward from 530 to 500 Ma to generate the voluminous *ca*. 500 Ma arc magmatism along the paleo-Pacific margin of Gondwana, or the Delamerian granites and Adelaide fold belt, triggering the broadly synchronous cessation of intra-Gondwana Pan-African deformation (Grunow et al., 1996). The mechanism seems to be impossible considering the remote distance from the margin, various thrust direction and intensity of deformation of the Pan-African event in EA, and the grantites from 550 to 480 Ma along the Transantarctic Mts, while the granites in EA younging to 500 Ma or even younger.

So, it is quite possible that the oblique convergence set the cratons into a series of counterrotating cogs which sheared the intervening fold belts, like the sinistral shear zones in SRMs (Toyoshima et al., 2013) and RSZ in southern Madagascar (Ishwar-Kumar et al., 2015). Anorogenic granites and associated metamorphic rocks were dotted around EA and the West African craton (Doblas et al., 2002).

Gondwana was buoyant, as indicated by small area of the platform sequence of nonmarine facies, meanwhile the Laurasia was depressed, as shown by marine facies (Veevers, 1995). As a supercontinent, the Gondwana lasted much longer than Laurasia and was hotter from internal heat, which may have been generated by mafic underplating during the Neoproterozoic-Cambrian Pan-African cycle. Gondwana buoyancy through changing the structure of the lower crust by mafic underplating may promote isostatic uplift and concomitant downwearing (Veevers, 2003, 1995). The Kalkarindji LIP in Australia was the oldest Phanerozoic LIP (*ca*. 512–509 Ma), which covers >2000000 km^2 at present (Jourdan et al., 2014). A crustal layer in the Australian Proterozoic shield with subhorizontal reflectors and velocity (V_p) >7.5 $km \cdot s^{-1}$ was interpreted as mafic underplating beneath latest Neoproterozoic flood basalt. The Pan-African terrane in East Africa also contains evidence of mafic underplating (Veevers, 1995). Recent progress was the increasing recognition of bimodal LIPs in Gondwana with significant, sometimes subequal, proportions of synchronous silicic volcanic rocks, mostly rhyolites to high silica rhyolites (±associated granitoids) to mafic volcanic rocks, not considered in mantle plume or plate process hypotheses. Several Gondwana LIPs erupted near the active continental margins, besides some within continents (Sensarma et al., 2018). As Veevers et al. (1997) pointed out, during the *ca*. 700–600 Ma period, the Gondwana and neighbouring continents mainly demonstrated as extensional state and deposited some glaciogenic sediments. Later at *ca*. 550 Ma, deformation by lateral shear in places (e.g., Petermann Ranges) and local sediments occurred during the Petermann orogeny, and the *ca*. 500 Ma deformation, granite intrusion and epeirogenic uplift of cratons. Events in East Gondwana accompanying the epeirogenic uplift of cratons at *ca*. 500 Ma included deformation, metamorphism, granite intrusion, being followed by a global sea-level maximum (Veevers, 2003).

Krabbendam and Barw (2000) stressed, convective removal of the thickened thermal boundary layer of the mantle lithosphere (TBL removal) and resulting orogenic collapse was a very efficient way of weakening the lithosphere. Small orogens (thickening factor < 1.5) that do not suffer TBL removal may remain lithospheric zones of strength long after orogenesis. While large, thick orogens may result in lithospheric zones of weakness and later break-up. In the Lurio Belt and the Nampula Complex, voluminous post-collisional magmatism younger than 530 Ma was present and was taken as evidence of gravitational collapse of the extensive orogenic domain south of the Lurio Belt after *ca*. 530 Ma (Bingen et al., 2009). In fact, the occurrence of the pulsive anorogenic granites and thermal events, gabbro, pegmatites, aulacogen-filled sediments and accompanying basement uplift and retrogressive metamorphism, demonstrates the extension-dominated tectonics, rather than the typically sequential deformation, metamorphism and magmatism activity in a normal orogenic belt.

The Precambrian basement of the External Hellenides was intruded by Cambrian granitoids (524 + 6/−5 Ma), which are frequent in the eastern Mediterranean, but are lacking in northern Africa. The granites may result from a Cadomian magmatic arc that occurred along the northern margin of East Gondwana. This arc was rifted off from Gondwana in Early Paleozoic times (Dörr et al., 2015). The occurrence of the unmetamorphosed Novillo mafic dyke swarms at 546±5 Ma in the Laramide belt in east-central Mexico indicates that the plume-related magmatism was related with separation of Avalonia from Oaxaquia (Keppie et al., 2006). A transtensional model was proposed by Keppie et al. (2003), in which a mid-ocean ridge collides with a subduction zone to produce a margin like that of present-day Baja California. The Avalonian age spectrum was similar to the Armorican one, but the latest age peaks of 570–550 Ma do not reflect an active plate margin but an extensional setting (Dörr et al., 2002; O'Brien et al., 1996).

Indeed, there were some sutures in the EA, like the presence of ophiolite and eclogite in the Shackleton Range (Schmädicke and Will, 2006). While most orogenies in the EA didn't show the rock association, and the collisional features were generally derived from the metamorphic PT paths (e.g., Liu et al., 2014a, 2009, 2007; Harley, 2003; Carson et al., 1997, 1995). Instead, most Pan-African orogenies in the EA show reworking features. Though with compressional structures, the orogenies generally show dominantly shearing and extensional structures. With some possible LIPs near the margin, the acompanying activity resulted in crustal reworking inside the Gondwana, and strong thermal effect and granitization. Intracrotonic origin was proposed for the Early Paleozoic Cathaysian orogeny along the SE margin of the Yangtze craton, although with typical ITD metamorphic path, granite emplacement and thrusting-thickening feature in deformation (Charvet et al., 2010). In central Australia, several significant intraplate reworking events, most notably the *ca*. 600–550 Ma Peterman orogeny occurred, accompanying the presence of the eclogites (Sandiford and Hand, 1998), and developed some sediments during the orogeny, with the unconformity between the Neoproterozoic and Early Cambrian (Camacho et al., 2002).

5 Conclusions

In summary, the following preliminary results have been obtained.

According to the granites and pegmatites, high-grade metamorphism and detrital zircon age peaks of the downflowing sediments from the plateau, the Pan-African event in the EA and adjacent areas was indicated as special zones or areas in many localities, including the coastal regions and interior of the EA. The event can be manifested by shear zones, granites and pegmatites, with local gabbros, mostly of amphibolite facies metamorphism, sometimes retrogressive metamorphism and accompanying resetting of some isotopic systems. The shear zones are present in many terranes in EA and adjacent blocks in Gondwana reconstruction, like the SE Africa, Madagascar, southern India and SW Australia. The granites are generally anorogenic, together with some gabbros or dolerite dykes, showing sign of collapse features of thickened continental crusts. The water or fluid available along the shear zones was responsible for retrogression of the earlier high grade Grenville outcrops to later Pan-African amphibolite to granulite facies metamorphism. Meanwhile, the Pan-African event has affected most isotopic systems, the zircon with grey or black CL images and younger apparent ages, the monazite and Sm-Nd, Rb-Sr, Ar-Ar mostly give the reset time of the Pan-African period. The mineral isochrons generally demonstrate larger area than the granite or metamorphism with the Pan-African event, suggesting the prevailing thermal effect in the period.

As regards the mechanism of the Pan-African event, it may overwhelmingly be an extensional and transcurrent tectonics. In the initial breakup period of the Rodinia, some sags or depressions may have been filled with sediments or glaciogenic deposits. The later Pan-Gondwana counter-rotating cogs shaped the interstitial fold belts between continent blocks and formed a set of shear zones. The mafic underplating in the Gondwana may be responsible for the typical features of the Pan-African event. That is to say, the event is a possible response of the plate movement surrounding the continent swarms in the non-stable interior of the yet consolidated Gondwana.

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